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Effects of Spatial Accumulation of Runoff on Watershed Response

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ABSTRACT

The drainage network accumulates upstream subwatershed runoff into a single downstream response, with runoff accumulating at network junctions. The effects of this accumulation on the magnitude and spatial variability of the downstream response are reviewed for simplified boundary conditions. Runoff parameters are runoff depth and corresponding unit area peak runoff rate. At the subwatershed level these parameters are referred to as *d* and *q*, respectively, and they vary from one subwatershed to another. At a downstream location, after accumulation by the drainage network, corresponding parameters are referred to as *D* and *Q*. Equations expressing the effects of runoff accumulation are formulated and discussed for uniform rainfall conditions. The review shows that the effects of runoff accumulation gain in importance as the number of upstream subwatersheds and the size of the watershed increase in the downstream direction. The accumulation process cancels extreme values of *d* and *q* to yield a representative *D* and *Q* value for the entire upstream drainage area. The impact of individual *d* and *q* values on the downstream *D* and *Q* values in the channel diminishes as the number of upstream subwatersheds increases. This results in a decrease in the spatial variability of *D* and *Q* in the downstream direction. The review suggests that the role of spatial variability of upstream *d* and *q* in the determination of downstream *D* and *Q* diminishes as watershed size increases. However, nonuniform rainfall distributions and storm movement may overshadow the effects of runoff accumulation when watershed size increases beyond the size of the storm.

STORM RUNOFF characteristics from small and large watersheds are generally different. At the field scale, runoff is sensitive to high rainfall intensities and land use (Chow, 1957; Beven et al., 1988). Response time is short, and runoff depth and unit area peak runoff rate are higher than for larger watersheds. At the basin scale, watersheds are aggregates of many contiguous subwatersheds. The runoff from these subwatersheds is collected by a network of channels, transferred downstream, and accumulated into a single watershed response. Channel, drainage network, and macroscale watershed characteristics control the runoff (Beven et al., 1988; Boyd, 1978; Gupta et al., 1980; Kirkby, 1976; Mesa and Mifflin, 1986; Rodriguez-Iturbe and Valdes, 1979). Response time is longer than for small watersheds, and runoff depth and unit area peak runoff rate decrease as drainage area increases (Linsley et al., 1975). Factors such as spatial variability of watershed characteristics and land use, nonuniform rainfall distribution, flood wave dissipation, subsurface return flow, and spatial runoff accumulation, among others, contribute to this change in runoff characteristics with watershed size.

The effects of spatial runoff accumulation by the drainage network have received comparatively little attention. In distributed models, these effects are implicitly included in the channel flow routing, and in lumped models they are included with other runoff processes in the input-response function. The closest direct representation of accumulation can be found in stochastic models based on basin geomorphology, such as by Rodriguez-Iturbe and Valdes (1979). In these models, watershed response is expressed in terms of drainage network parameters. However, the effects of accumulation are still imbedded in relations that include other network influences.

Yet, as watersheds with drainage networks are being modeled, the effects of spatial runoff accumulation may become relevant to the modeling approach (Dooge, 1986) and one needs to be aware of their impact on runoff characteristics. The extent to which the spatial variability of subwatershed runoff affects the watershed response, and how this response changes in the downstream direction is largely defined by the runoff accumulation. As a contribution to this special issue on cumulative watershed effects, the role of spatial runoff accumulation by the drainage network and its effects on watershed runoff depth and unit area peak runoff rate are reviewed for simplified boundary conditions and illustrated by a hypothetical example.

SCOPE

Simplifying assumptions are necessary to isolate the effects of spatial runoff accumulation from other runoff modifying factors such as nonuniform rainfall distribution, storm movement and flood wave dissipation. The drainage network is assumed to be conservative, i.e., there is no loss from the channels to the groundwater, or vice versa. This assumption is not restrictive for storm runoff, except in regions with significant transmission losses. The drainage network is assumed devoid of lakes, reservoirs, or storage intensive flood plains. As a result hydrograph diffusion is negligible and the hydrograph transformation in the channels is primarily controlled by the drainage network topology (Garbrecht, 1988). The rainfall timing, duration, and intensity are assumed uniform over the watershed to eliminate any bias due to rainfall distribution pattern and storm movement. This assumption puts an upper limit on the watershed size for this review. Only surface runoff from excess rainfall is considered. Finally, the movement of channel runoff is modeled by linear translation, and the linearity and superposition principles apply.

Within this conceptual setting, watershed, drainage network, and number, size and spatial distribution of the subwatersheds are assumed known. Subwatershed runoff depth (d) and corresponding unit area peak runoff rate (q), also assumed known, are the input into the drainage network and represent the independent variables of the study. The d and q differ from one subwatershed to another due to spatial variability in subwatershed geometry, land use, soils, and antecedent moisture conditions. The downstream accumulated runoff depth (D) and corresponding accumulated unit area peak runoff rate (Q) are the unknown de-

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pendent variables. They change in the downstream direction along the drainage network and define the effects of spatial variability and spatial runoff accumulation on downstream response.

The runoff parameters, d, q, D and Q, are expressed on a unit area basis to remove their dependence on drainage area. Indeed, total runoff volume and total peak runoff rate (not per unit area) generally increase with increasing upstream drainage area (Linsley et al., 1975). The unit area approach brings nontrivial effects of accumulation to light.

RUNOFF DEPTH

Runoff depth is the excess rainfall depth from a single storm event. It is a conservative parameter in the sense that it does not dissipate or amplify as the runoff travels through the drainage network. As a result the accumulation of runoff depth can be derived from mass conservation alone:

$$D = \frac{1}{A} \sum_{i=1}^{n} [A_i d_i] \qquad [1]$$

where D is downstream accumulated runoff depth, d is subwatershed runoff depth, A is drainage area, subscript i is subwatershed identifier, and n is number of subwatersheds. According to Eq. [1], D is the area weighted average of d_i. Hence, contributions from larger subwatersheds dominate over those from smaller ones. If all subwatersheds were equal in size, D would simply be the arithmetic mean of d. Under these conditions the variability of d about the mean is not a factor in the determination of D. However, it becomes a factor when it is weighted by the subwatershed area. Therefore, spatial variability of d affects the magnitude of D only through the variability of the size of upstream subwatershed areas.

Runoff accumulation results in a loss of information in the downstream direction. Once accumulated, the d_i lose their identity and cannot be redefined from D alone. In other words, many different combinations of d_i can produce the same D value. Therefore, the loss of information by runoff accumulation affects primarily information on spatial variability, yet the mean representative value for the upstream drainage area is retained.

Runoff accumulation also affects the spatial variability of D in the downstream direction. This variability depends on the number of upstream subwatersheds and on the variability of the d_i. At the top of the drainage network, where subwatersheds are few, channel runoff is sensitive to new subwatershed input. A subwatershed with a large d can cause a substantial increase in D. This is because new contributions still represent a significant portion of the channel runoff. As the number of upstream subwatersheds increases, D becomes less and less sensitive to new additions of d, and it stabilizes at a value reflecting overall upstream conditions. This is the result of the "Law of Large Numbers," which states that the larger the system, the more likely one is to obtain a value close to the predicted average. Hence, runoff accumulation reduces the spatial variability of D in the downstream direction, and it forces it to converge to a representative value for the entire upstream watershed. Similar conclusions have been reached by Wood et al. (1988), using numerical rainfall-runoff modeling on the Coweeta River experimental catchment in North Carolina.

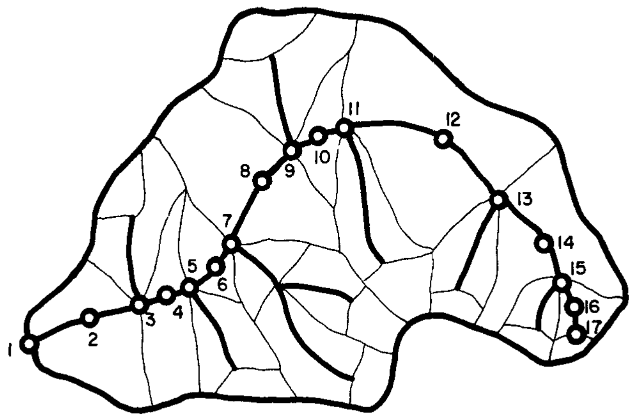

Fig. 1. Hypothetical watershed with third-order drainage network and 26 subwatersheds. The numbers on the figure represent locations at which runoff depths and peak flow rates are computed.

The variability of D along the drainage network is illustrated for a hypothetical watershed. The watershed and corresponding drainage network are depicted in Fig. 1 and pertinent data are given in Table 1. Watershed and drainage network configurations are arbitrary. Even though the specific values of D and Q depend upon these configurations, it is believed that the trend of the data in the downstream direction, which is the emphasis of this article, is representative for most watersheds and drainage networks fitting the framework of this review. Under real world conditions, additional flow modifying effects, such as those due to nonuniform rainfall distribution and storm movement, must be included. However, the objective

Table 1. Watershed and runoff data for the watershed depicted in Fig. 1. Locations are shown in Fig. 1 and the LR coefficient is defined in the section on peak runoff rate.

Location	Distance from outlet	Upstream drainage area	No. of upstream subwatersheds	Average area weighted LR coefficient	Runoff depth	Peak rate
	km	ha			mm	mm/h
1	0.00	820	26	0.845	27.18	10.2
2	0.39	820	26	0.845	27.18	10.2
3	0.81	766	25	0.835	26.67	9.9
4	1.14	718	23	0.832	26.42	9.6
5	1.32	676	22	0.821	26.67	9.6
6	1.59	635	20	0.818	26.42	9.5
7	1.80	612	19	0.819	26.16	9.2
8	2.22	501	14	0.826	26.92	9.0
9	2.73	401	13	0.807	24.89	8.6
10	2.94	335	11	0.771	24.38	8.5
11	3.12	312	10	0.768	24.64	7.8
12	3.75	255	8	0.718	26.92	7.7
13	4.32	128	7	0.754	22.61	11.2
14	4.56	94	5	0.615	21.34	10.1
15	4.92	31	4	0.952	31.75	25.4
16	5.13	14	2	0.906	25.65	20.3
17	5.31	3	1	1.000	29.72	37.8

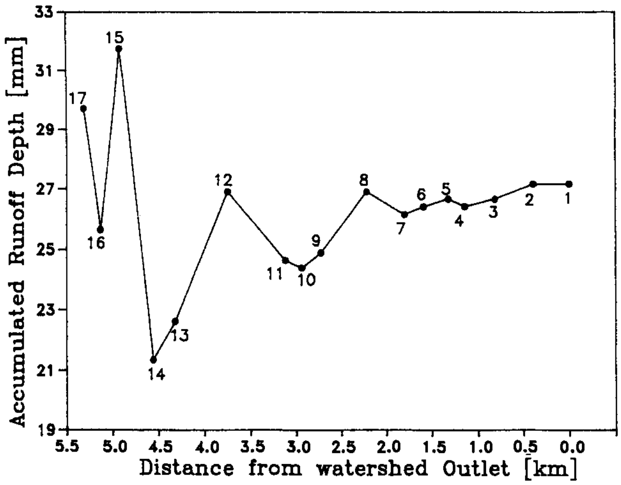

Fig. 2. The value of D as a function of distance down the drainage network. The numbers on the figure represent the location on the drainage network at which D is computed (see Fig. 1).

here is to isolate and illustrate the effects of runoff accumulation only.

The d values in the application example vary from one subwatershed to another for reasons previously discussed. They are modeled in this application as randomly generated values between 12 and 38 mm. This rather wide range of d values is intentionally introduced to produce significant spatial variability in this parameter. The resulting trend for D in the downstream direction is depicted in Fig. 2. The decrease in spatial variability of D in the downstream direction is clearly visible. At the top of the drainage network, D varies considerably as the d values from new subwatersheds are added. However, as the number of subwatersheds and the upstream drainage area increase, the spatial variability of D rapidly decreases toward a weighted average D value representing the conditions of the entire upstream drainage area.

Nonuniform rainfall distribution changes the spatial variability of d. However, previous findings still apply because Eq. [1] is independent of the cause of the spatial variability. Also, D generally decreases as watershed size increases beyond the storm size because the number of subwatersheds with little or no runoff increases and their contribution results in a smaller D. This reduction in D as a function of increasing drainage area is generally observed in natural watersheds (Baumgartner and Liebscher, 1990).

PEAK RUNOFF RATE

The time distribution of subwatershed surface runoff is a simple hydrograph with a single peak. The subwatershed hydrographs enter the drainage network, travel downstream, and reach the watershed outlet at different times because the travel distance from subwatershed to watershed outlet is different for each subwatershed. As a result subwatershed hydrographs are lagged with respect to each other. The interplay between the spatial distribution of the subwatersheds,

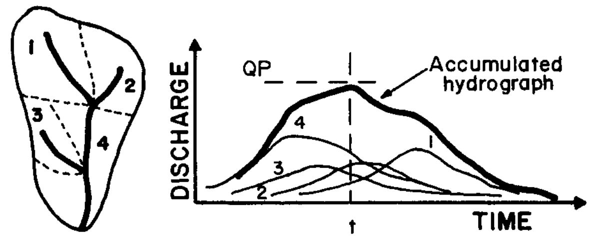

Fig. 3. Schematic of the interplay between spatial distribution of subwatersheds, hydrograph timing, and accumulated hydrograph.

the hydrograph translation, and the timing of the hydrographs at a downstream location is depicted in Fig. 3 for a simple case of four subwatersheds. The runoff from Subwatershed 4 arrives first at the watershed outlet, followed closely by the runoff from Subwatershed 3, then 2, and last, 1. The sum of the four subwatershed hydrographs yields the watershed response and defines its time to peak and total peak runoff rate (not per unit area). Based on this model, Q at a downstream location is given as the area weighted sum of the q_i with appropriate reduction to account for the relative lag between the subwatershed hydrograph

$$Q = \frac{1}{A}\sum_{i=1}^{n}[c_iA_iq_i] \qquad [2]$$

where Q is downstream accumulated unit area peak runoff rate, q is the subwatershed unit area peak runoff rate, and c is the lag-reduction (LR) coefficient. All other variables have been defined earlier. The LR coefficient expresses the effect of hydrograph timing by defining the fraction of q that contributes to Q. It is determined independently from hydrograph shape and time between the translated subwatershed and downstream hydrograph peaks (see Fig. 3)

$$c_i = q_{i,t}/q_i \qquad [3]$$

where $q_{i,t}$ is the discharge of subwatershed hydrograph i at time t (at the downstream location), t is the time at which Q occurs at the downstream location, and q_i was defined previously. The LR coefficient, c_i, is always ≤ 1.

According to Eq. [2], Q at any given location along the drainage network is the area and lag weighted average of the upstream q_i. The weighting by the area and the LR coefficient provides the only link between the spatial variability of q and the magnitude of Q. The effect of area weighting has been discussed earlier for runoff depth (Eq. [1]). As for the LR coefficient, it places more weight on the subwatershed hydrographs whose timing coincide with the accumulated hydrograph. These subwatersheds are generally those located close to the centroid of the watershed. Also, the loss of upstream information due to spatial runoff accumulation, as discussed for runoff depth, applies to peak runoff rate.

Other differences with Eq. [1] are brought about by the LR coefficient. The coefficient reduces the contribution of q to Q due to the hydrograph timing. The effect of hydrograph timing has been presented previously by Leopold (1974). The amount of reduction depends on the shape of the subwatershed hydrographs and on the spatial distribution of the subwatersheds within the basin. For a given spatial subwatershed distribution and hydrograph timing, long and flat hydrographs tend to overlap and have LR coefficients closer to 1, whereas narrow and steep hydrographs are more staggered and have comparatively smaller LR coefficients. On the other hand, for given hydrograph shapes, an increase in distance between subwatersheds results in a larger separation between hydrographs and smaller LR coefficients. This is the reason why, under uniform rainfall conditions, elongated watersheds produce a much flatter response than circular watersheds of the same area (Baumgartner and Liebscher, 1990). From this discussion, it is clear that the effects of hydrograph timing and subwatershed distribution, particularly when small LR coefficients are involved, may dominate over the effects of spatial runoff accumulation.

Changes in Q in the downstream direction are twofold. First, there is a decrease in variability of Q in the downstream direction due to spatial runoff accumulation. This decrease is related to the Law of Large Numbers as previously discussed for runoff depth (Eq. [1]). Second, the magnitude of Q decreases in the downstream direction because the upstream drainage area increases faster than Q does. The smaller increase of Q is attributed to the early timing of the hydrographs from new subwatersheds that are included as one moves in the downstream direction. The hydrograph from these subwatersheds reach the downstream location earlier than the accumulated hydrograph, and, therefore, contribute relatively less to Q than the hydrographs from subwatersheds close to the centroid of the watershed. Therefore, under uniform rainfall conditions, the decrease in Q in the downstream direction is attributed to an increase in the range of hydrograph staggering due to the spatial subwatershed distribution.

The behavior of Q is illustrated in Fig. 4 for the watershed depicted in Fig. 1. The subwatershed hydrograph shapes and q_i are developed using the SCS synthetic unit hydrograph method and given runoff depths. Subwatershed hydrographs at a downstream location are lagged with respect to each other to reflect the different times of arrival resulting from the spatial subwatershed distribution. The example application shows the decrease in variability and magnitude of Q in the downstream direction. The drop in magnitude of Q is quite rapid in the upstream portion of the watershed because the randomly generated q for subwatersheds at locations 14 and 12 happen to be small. Coupled with their respective large drainage areas, the q values from these two subwatersheds overshadow the contributions from the smaller upstream subwatersheds. The value of Q recovers only slightly from this influence as the runoff from subwatersheds below location 7 are included.

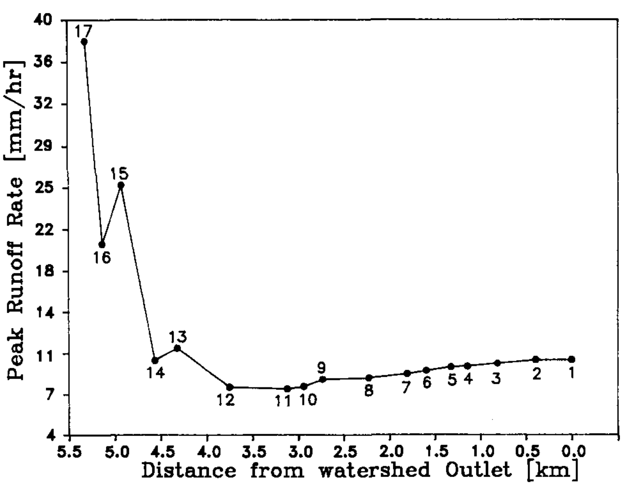

Fig. 4. Variation of Q as a function of distance down the drainage network. The numbers on the figure represent the locations along the drainage network where Q is computed (see Fig. 1).

Under natural conditions the nonuniform rainfall distribution further contributes to the downstream decrease in Q. This follows from the fact that, as the watershed size increases beyond the storm size, the subwatersheds with little or no runoff have an increasing attenuating effect on Q. Storm movement is also an important factor, as it redefines the hydrograph timing and the LR coefficients. If the storm moves with the runoff in a downstream direction, the lag between the subwatershed hydrographs is reduced and a larger Q can be expected than if the storm moves in the opposite direction (Baumgartner and Liebscher, 1990). This again shows that as the size of the watershed increases, effects of storm size, distribution, and movement may become dominant factors over spatial variability in subwatershed runoff due to physiographic factors.

SUMMARY AND CONCLUSIONS

The effects of spatial runoff accumulation by the drainage network on watershed response is reviewed. The runoff parameters are the runoff depth, d and D, and corresponding unit area peak runoff rate, q and Q. They are assumed to be known at the subwatershed level and represent the independent variables. Rainfall is assumed uniform and the spatial variability in d and q is the result of varying physiographic subwatershed characteristics. The effects of spatial runoff accumulation are isolated using simplified boundary conditions and analyzed independently of other runoff modifying factors. They are defined by changes in the magnitude and spatial variability of D and Q in the downstream direction.

The value of D at any location on the drainage network is the area weighted average of the upstream d_i. It is a representative value for the entire upstream drainage area. As a result of area weighting, the spatial variability of d affects the magnitude of D only through the variability of the size of the subwatershed areas. It was also found that the spatial variation of D diminishes in the downstream direction. This reduction in variability is the direct result of runoff accumulation. It is related to the Law of Large Numbers and results in a loss of information with respect to the spatial variability of d.

The value of Q at any location on the drainage network is the area and LR coefficient weighted average of the upstream q_i. The relative lag of the subwatershed hydrographs with respect to each other and the hydrograph shapes are critical in determining Q. Differences in hydrograph timing are the result of the spatial distribution of the subwatersheds within the basin. As watershed size increases the range of hydrograph spacing among each other increases and hydrographs from subwatersheds that are located far from the watershed centroid contribute comparatively less to Q than hydrographs from subwatersheds close to the centroid. Coupled with the steady increase in drainage area in the downstream direction, this results in the magnitude of Q to generally decrease in the downstream direction. As for runoff depth, the spatial variability in Q diminishes in the downstream direction.

Within the conceptual setting of this review, D and Q are the result of a complex interplay between the spatial variability of d and q and the effects of spatial runoff accumulation. The effects of spatial runoff accumulation are twofold. First, at a location, they integrate all upstream conditions into a representative downstream value. Spatial variability of subwatershed runoff plays a secondary role in favor of number, size, and spatial distribution of subwatersheds. And, second, spatial variation of D and Q diminishes in the downstream direction. From these results it is inferred that: (i) runoff from watersheds is generally the expression of the overall watershed characteristics; (ii) the importance of spatial variability of subwatershed runoff on the downstream runoff is diminished by the spatial runoff accumulation; and (iii) effects of spatial runoff accumulation, nonuniform rainfall distribution, and storm movement gain in importance over subwatershed runoff characteristics as the watershed size increases. This review provides qualitative information on the effects of spatial runoff accumulation and may help determine a modeling approach when runoff accumulation by the drainage network is an important component of the hydrologic system.

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